

FLAVOR CHANGING NEUTRAL CURRENTS AND THE THIRD FAMILY

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Abstract: We consider a Two Higgs Doublet Model with Flavor Changing Scalar Neutral Currents arising at the tree level. All the most important constraints are taken into account and the compatibility with the present Electroweak measurements is examined. The Flavor Changing couplings involving the third family are not constrained to be very small and this allows us to predict some interesting signals of new physics. (This paper relies on some work done in collaboration with D. Atwood (CEBAF) and A. Soni (BNL)).

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All processes involving Flavor Changing Neutral Currents (FCNC) are suppressed in the Standard Model (SM) because they are forbidden at the tree level. Some of them end up having a measurable, although small, branching fraction since they are enhanced at the loop level by the presence of a top quark in the loop. This is the case of some radiative B -meson decays, like those induced at the parton level by $b \rightarrow s\gamma$ ($Br(B \rightarrow X_s\gamma) \sim 10^{-4}$ [1]). However, a similar enhancement cannot take place for the up-type FC transitions and therefore this can be a good place to look for evidence of new physics.

Moreover, the outstanding nature of the top quark (with its huge mass, $m_t \sim 175$ GeV) should induce us to reexamine our theoretical prejudices about the existence of Flavor Changing Scalar Interactions (FCSI), especially for the top quark itself. Probing the top-charm and top-up flavor changing vertex consequently deserves a special attention. We will present a theoretical model in which FCSI can be generated at the tree level with a given hierarchy and discuss some possible experimental environments in which definite bounds on the top quark FC couplings can be put.

We will consider a Two Higgs Doublet Model (2HDM) with allowed FCNC in the scalar sector, the so called Model III [2]. In fact, in models with a non-minimal Higgs sector, e.g. in the 2HDM, FCSI arise readily at the tree level. In order to avoid the severe constraints from $K^0 - \bar{K}^0$ and $B^0 - \bar{B}^0$ mixing, it was originally proposed [3] to forbid all FCSI by imposing a suitable discrete symmetry acting on the quark and the scalar fields [4]. However, as later realized by many authors [5], it is possible to remove the *ad hoc* discrete symmetry and satisfy the constraints by choosing an adequate ansatz on the FC couplings. In particular, it was observed that the necessary hierarchy on the FC couplings between fermions and scalars is provided by the mass parameters of the fermion fields themselves [5]. If this is the case, then the top quark FC couplings can be greatly enhanced with respect to the first and second generation ones.

In some recent papers [6, 7, 8], we have analyzed in detail this kind of 2HDM and studied the possible phenomenological implications that large FC top couplings can have. Due to the theoretical and experimental interest of this analysis, we want to provide a brief but comprehensive description of Model III and of the most important constraints that affect its FCSI. Given the constrained Model, we will proceed to the discussion of some clean experimental environments in which signals from FCSI can be detected.

Let us focus on the quark Yukawa interactions only and write the corresponding Yukawa Lagrangian for a 2HDM in the following very general form [2]

$$\mathcal{L}_Y = \eta_{ij}^U \bar{Q}_i \tilde{\phi}_1 U_j + \eta_{ij}^D \bar{Q}_i \phi_1 D_j + \xi_{ij}^U \bar{Q}_i \tilde{\phi}_2 U_j + \xi_{ij}^D \bar{Q}_i \phi_2 D_j + h.c. \quad (1)$$

where ϕ_i for $i = 1, 2$ are the two scalar doublets, while $\eta_{ij}^{U,D}$ and $\xi_{ij}^{U,D}$ are the non diagonal coupling matrices. By a suitable rotation of the fields we chose the physical scalars in such a way that only the $\eta_{ij}^{U,D}$ couplings generate the fermion masses, i.e. such that

$$\langle \phi_1 \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \quad \langle \phi_2 \rangle = 0 \quad (2)$$

The physical spectrum consists of two charged ϕ^\pm and three neutral spin 0 bosons, two scalars (H^0, h^0) and a pseudoscalar (A^0)

$$\begin{aligned} H^0 &= \sqrt{2}[(\text{Re } \phi_1^0 - v) \cos \alpha + \text{Re } \phi_2^0 \sin \alpha] \\ h^0 &= \sqrt{2}[-(\text{Re } \phi_1^0 - v) \sin \alpha + \text{Re } \phi_2^0 \cos \alpha] \\ A^0 &= \sqrt{2}(\text{Im } \phi_2^0) \end{aligned} \quad (3)$$

where α is a mixing phase (for $\alpha=0$, H^0 corresponds exactly to the SM Higgs field, and ϕ^\pm , h^0 and A^0 generate the new FC couplings). In principle the $\xi_{ij}^{U,D}$ FC couplings are arbitrary, but reasonable arguments exist to adopt the following ansatz [5]

$$\xi_{ij}^{U,D} = \lambda_{ij} \frac{\sqrt{m_i m_j}}{v} \quad (4)$$

where for the sake of simplicity we take the λ_{ij} parameters to be real (for more details see [6, 8]). Alternatively, we can assume the $\xi_{ij}^{U,D}$ to be purely phenomenological couplings and try to constrain them from experiments. In fact, the two assumptions are almost equivalent, as far as one keeps a certain arbitrariness on the parameters λ_{ij} of eq.(4). What is really crucial to our analysis is to derive a consistent scenario in which each FC coupling of Model III is constrained from some existing phenomenology.

From a detailed analysis¹ [6], we obtain that ξ_{ds} and ξ_{db} are constrained to be very small by the experimental measurement of the $K^0 - \bar{K}^0$ ($\Delta M_K^{exp} = 3.51 \times 10^{-15}$ GeV) and $B^0 - \bar{B}^0$ ($\Delta M_B^{exp} = 3.36 \times 10^{-13}$ GeV) mixings². To a less extent the $D^0 - \bar{D}^0$ mixing ($\Delta M_D^{exp} \leq 1.32 \times 10^{-13}$ GeV) also constrains ξ_{uc} to be small and it is likely to give a bound as severe as the ones from the previous two mixings as soon as the experimental precision improves by an extra order of magnitude. Almost all the FC couplings involving the first generation are therefore immediately suppressed, confirming the hierarchical nature of the FCSI of Model III. Hence, we can make the more general assumption that all the FC couplings involving the first generation are almost negligible, extending the previous bounds also to $\xi_{ut}^{U,D}$, even if we do not have any direct constraint at the moment.

The loop contributions to the previous $F^0 - \bar{F}^0$ mixings and the $Br(B \rightarrow X_s \gamma)$ put limits on the remaining $\xi_{ij}^{U,D}$ couplings. In particular, it turns out that they can be well

¹In our analysis the masses of the scalar particles are let vary in the range $200 \text{ GeV} < M_s < 1 \text{ TeV}$ and the phase α is taken to be $\alpha = 0, \pi/4$.

²In a Model with FCSI a process like $F^0 - \bar{F}^0$ mixing occurs at the tree level and, unless unusual assumptions on the FC couplings are made, this constitutes the leading contribution.

described by the ansatz in eq.(4), when the corresponding λ_{ij} parameters vary in the range $0.1 < \lambda_{ij} < 10$. In this way the hierarchy of the FC couplings is still guaranteed.

Moreover, the analysis of the $Br(B \rightarrow X_s \gamma)$ and of the ρ parameter³ (see ref. [8] for full details) selects a specific region of the scalar mass parameter space. The charged scalar mass has to be $M_c > 600$ GeV and one of the following conditions

$$M_H, M_h \leq M_c \leq M_A \quad \text{and} \quad M_A \leq M_c \leq M_H, M_h \quad (5)$$

has to be verified, where M_H and M_h are the masses of the neutral scalars H^0 and h^0 and M_A is the mass of the neutral pseudoscalar A^0 , as in eq.(3).

Within this version of Model III we can now draw the attention to some interesting process that could help to constrain the third family FC couplings. We think that top-charm production at a high energy lepton collider, i.e. e^+e^- , $\mu^+\mu^- \rightarrow \bar{t}c + \bar{c}t$, can be very distinctive under many respects. First of all, this is the kind of process whose SM prediction is extremely suppressed [6] and any signal would be a clear evidence of new physics with large FC couplings in the third family. Second, it has a very clean kinematical signature, with a very massive jet recoiling against an almost massless one (very different from a bs FC signal, for instance). This characteristic is enhanced even more in the experimental environment of a lepton collider, because of the very low background. Apart from these general considerations, the cases of an e^+e^- collider and of a $\mu^+\mu^-$ collider require a separate analysis.

At an e^+e^- collider the tc -production process arises at the one loop level via $e^+e^- \rightarrow \gamma^*, Z^* \rightarrow \bar{t}c + \bar{c}t$. The tree level FC processes generated by the s-channel exchange of a scalar boson (h^0, \dots) are suppressed due to the smallness of the electron mass. The effective γtc and Ztc vertices can be calculated at one loop [6] and used in the calculation of the cross section. Of particular relevance is the normalized ratio

$$R_{tc} \equiv \frac{\sigma(e^+e^- \rightarrow \bar{t}c + \bar{c}t)}{\sigma(e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-)} \quad (6)$$

We will assume for purpose of illustration a common value of λ_{ij} for all the $\xi_{ij}^{U,D}$ couplings involved. The ratio R_{tc} scales as λ^4 , therefore our predictions crucially depend on the value of the arbitrary parameter λ . In particular, R_{tc} is governed, in the mass parameter range of eq.(5), by ξ_{tt} and ξ_{tc} and $e^+e^- \rightarrow \bar{t}c + \bar{c}t$ will be an important process to constrain the magnitude of these non standard couplings. As an example we plot in Fig. 1 the ratio R_{tc} normalized to λ^4 as a function of \sqrt{s} . We look in particular to the case in which one scalar mass is light ($M_l \sim 200$ GeV) and the other two are much heavier ($M_h \sim 1$ TeV), which could correspond to one of the two conditions in eq.(5). As we can see from Fig. 1 there is no need to increase \sqrt{s} above 500 GeV, where $10^4 - 10^5 \mu^+\mu^-$ are predicted.

³We recall that $\rho = M_W^2/(c_W^2 M_Z^2)(1 + \Delta\rho_0)$ where $\Delta\rho_0$ parametrizes the deviation from the SM result.

We can see that for values of λ a little bigger than unity a few events can be seen. Since there is no experimental basis for assuming the absence of tree level FCNC at the scale m_t , their rigorous search is strongly advocated.

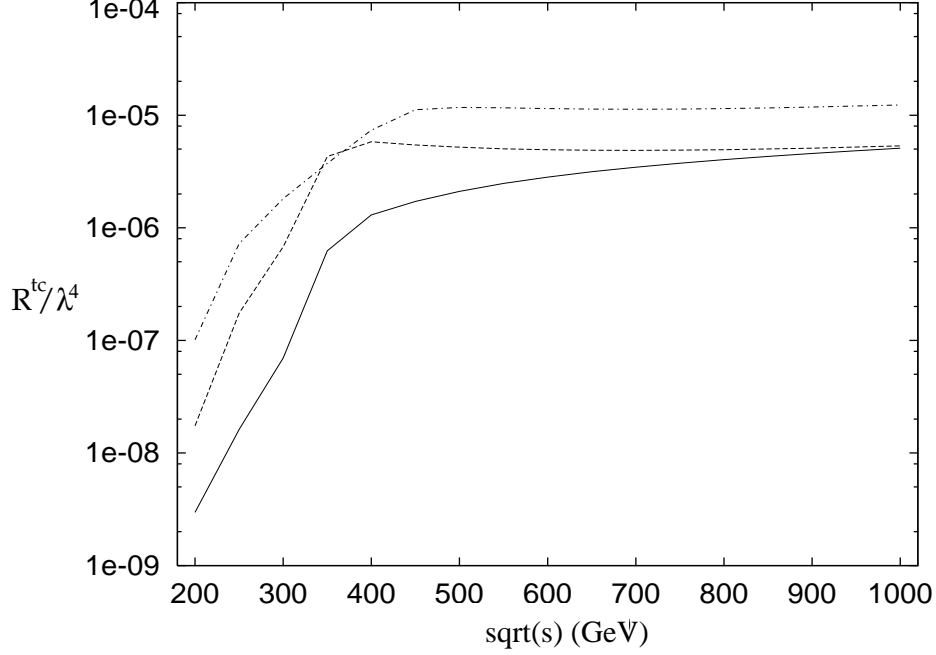


Figure 1: R_{tc}/λ^4 vs. \sqrt{s} when $M_h = 200$ GeV and $M_A \simeq M_c = 1$ TeV (solid), $M_A = 200$ GeV and $M_h \simeq M_c = 1$ TeV (dashed), $M_c = 200$ GeV and $M_h \simeq M_A = 1$ TeV (dot-dashed).

Another interesting possibility to study top-charm production is offered by Muon Colliders [7]. Although very much in the notion stage at present, $\mu^+\mu^-$ colliders has been suggested as a possible lepton collider for energies in the TeV range [9]. Most of the applications of Muon Colliders would be very similar to electron colliders. One advantage, however, is that they may be able to produce Higgs bosons (\mathcal{H}) in the s channel in sufficient quantity to study their properties directly (remember that $m_\mu \simeq 200 m_e$). The crucial point is also that in spite of the fact that the $\mu^+\mu^-\mathcal{H}$ coupling, being proportional to m_μ , is still small, if the Muon Collider is run on the Higgs resonance, $\sqrt{s} = m_{\mathcal{H}}$, Higgs bosons may be produced at an appreciable rate.

We have considered [7] the simple but fascinating possibility that such a Higgs, \mathcal{H} , has a flavor-changing $\mathcal{H}t\bar{c}$ coupling, as is the case in Model III or in any other 2HDM with FCNC. As we did for the e^+e^- case, also in the $\mu^+\mu^-$ case we can define the analogous of R_{tc} in eq.(6) to be

$$\tilde{R}_{tc} = \tilde{R}(\mathcal{H}) (B_{t\bar{c}}^{\mathcal{H}} + B_{c\bar{t}}^{\mathcal{H}}) \quad (7)$$

where $\tilde{R}(\mathcal{H})$ is the effective rate of Higgs production at a Muon Collider and $B_{t\bar{c}}^{\mathcal{H}}$ or $B_{c\bar{t}}^{\mathcal{H}}$ denote the branching ratio for $\mathcal{H} \rightarrow t\bar{c}$ and $\mathcal{H} \rightarrow c\bar{t}$ respectively. Assuming that the background will be under reasonable control by the time they will start operate a Muon Collider, our estimate is that $10^{-3} < \tilde{R}_{tc} \leq 1$, depending on possible different choices of the parameters. For a Higgs particle of $m_{\mathcal{H}} = 300$ GeV, a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and a year of 10^7 s (1/3 efficiency), a sample of tc events ranging from almost one hundred to few thousands can be produced [7]. Given the distinctive nature of the final state and the lack of a Standard Model background, the predicted luminosity should allow the observation of such events. Therefore many properties of the Higgs- tc coupling could be studied in detail.

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